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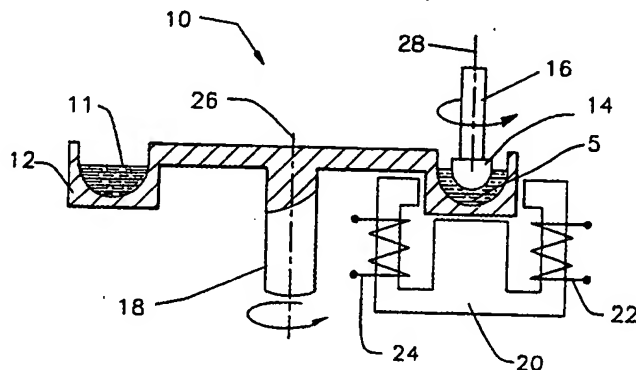
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(57) Abstract

A method of polishing an object is disclosed. In one embodiment, the method comprises the steps of bringing the object (14) into contact with a fluid (11); moving at least one of the object (14) or fluid (11) with respect to the other; and varying the consistency of the fluid in a region wherein the object is located. Also disclosed is a polishing device (10). In one embodiment the device comprises a vessel (12) for holding a polishing fluid (11); a mount (16) for receiving an object (14) to be polished, said mount (16) adapted for positioning the object in contact with the fluid (11); means for moving at least one of the fluid (11) and mount (16) with respect to the other; and means for varying the consistency of the fluid (11) in a region containing the mount (16).

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MAGNETORHEOLOGICAL POLISHING DEVICES AND METHODS

This application is a continuation-in-part of pending U.S. Serial No. 868,466, filed April 14, 1992.

FIELD OF THE INVENTION

This invention relates to methods of polishing surfaces using magnetorheological fluids, and fluids used therein.

5

BACKGROUND OF THE INVENTION

Work-pieces such as glass optical lenses, semiconductors, tubes and ceramics have been polished in the art using one-piece polishing tools made of resin, rubber, polyurethane or other solid materials. The working surface of the polishing tool should conform to the work-piece surface. This makes polishing complex surfaces complicated, and difficult to adapt to large-scale production. Additionally, heat transfer from such a solid polishing tool is generally poor and can result in superheated and deformed work-pieces and the surface of the polishing tools, thus causing damage to the geometry of the work-piece surface and/or the tool.

Simjian, U.S. Patent No. 2,735,232, describes a device for polishing or surface-abrading articles by immersing the object to be polished in a bath containing magnetic particles. The fluid in the polishing bath varies in viscosity when subject to the application of a magnetic field. Simjian discloses a polishing bath consisting of an abrasive

powder such as Carborundum, a magnetic powder such as iron filings, and a liquid which may be any type of lubricating oil. This mixture is housed in a container and the article to be polished is immersed in the mixture. An alternating
5 polyphase magnetic field is applied to the mixture. Simjian discloses that the magnetic field may be set up such that a rotating magnetic field results. This in turn acts upon the magnetic particles and causes them to turn in small circles, the diameter of which depends upon the viscosity of the
10 liquid, frequency of the alternating magnetic field, and the strength of the magnetic field. This spinning of the magnetic particles carries the abrasive particles into motion which causes the polishing or abrading action. Simjian also discloses that uniform polishing may be obtained by rotating
15 the work-piece in the bath.

The device described by Simjian has limited applicability. Alternating magnetic fields generally generate particle suspension velocities insufficient for acceptable polishing. Simjian's use of alternating magnetic fields is
20 also generally unacceptable for polishing a work-piece with a complex geometry surface because of the difficulty of providing uniform contact between the work-piece and the polishing medium. Simjian also does not provide for the removal of excess heat generated by the polishing process,
25 thereby neither allowing fluid velocities sufficient for desirably rapid polishing nor protecting the work-piece from thermal damage.

Kato, U.S. Patent No. 4,821,466 describes a device

for polishing articles utilizing an abrasive-containing magnetic fluid. The work-piece to be polished is immersed in the abrasive-containing magnetic fluid. A floating pad is positioned adjacent to the work-piece and is given a buoyant
5 force by a magnetic field that is supplied from the outside of the container. The buoyant force of the pad forces abrasive particles located in the magnetic fluid between the work-piece and the pad against the work-piece. The mutual motion of the work-piece and the magnetic fluid containing abrasive grains
10 accomplishes the polishing. The mutual motion between the work and the abrasive grains in the magnetic fluid may be accomplished by a revolution, a vibration or other kind of motion of the work-piece or by a reciprocation, a revolution or a vibration of the magnetic fluid by actuating the magnetic
15 field or by a combination of these motions.

The device described by Kato also suffers from drawbacks such as an undesirably coarse finish to the work-piece. The Kato process also is limited to flat surfaces with polishing of complex geometry surfaces being very difficult.
20 Additionally, Kato et al. does not disclose means for removing excess heat generated by the polishing process, thereby limiting the rate at which a work-piece may be polished in order to avoid thermal damage to the work-piece.

25 SUMMARY OF THE INVENTION

This invention is directed to a device and method for polishing objects in a magnetorheological polishing fluid (MP-fluid). The method comprises the steps of bringing said

object into contact with a fluid; moving at least one of said object and said fluid with respect to the other; and varying the consistency of said fluid in a region wherein said object is located. The polishing vessel can be a circular vessel
5 with an annular cavity in which the magnetorheological polishing fluid is contained. In this embodiment, the vessel and the MP-fluid are put into rotation. The object to be polished is attached to a spindle which can spin about its axis. The object to be polished is immersed in the MP-fluid
10 and spun, thereby allowing all facets of the object to be exposed to the oncoming MP-fluid in the rotating vessel. The MP-fluid can contain an abrasive suspension, a chemical solvent or both.

The fluid is acted upon by a magnetic field in the
15 region that the fluid contacts the object to be polished. The magnetic field causes the MP-fluid to acquire the characteristics of a plasticized solid whose yield point depends on the magnetic field intensity and the viscosity. The yield point of the fluid is high enough that it forms an
20 effective polishing surface, yet still permits movement of abrasive particles. The effective viscosity and elasticity of the MP-fluid when acted upon by the magnetic field provides resistance to the abrasive particles such that the particles have sufficient force to abrade the work-piece.

25 In another embodiment, a polishing device comprises a plurality of lines for delivering a polishing fluid to a tubular work-piece and a means for connecting the tubular work-piece to the delivery lines. The connection can be

adapted so that said tubular work-piece may move slidably and rotatably. In this embodiment the tubular work-piece and the MP-fluid may be moved with respect to the other. Once the MP-fluid is in the tubular work-piece, a magnetic field may act
5 upon the MP-fluid causing it to acquire the characteristics of a plasticized solid polishing surface. This change in consistency provides resistance to the abrasive particles such that the particles have sufficient force to abrade the inner surface of the tubular work-piece.

10

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a cross-sectional side view of an apparatus of the invention useful for polishing work-pieces.

Figure 2 is a top planar view of the fluid vessel of the invention.

15

Figure 3 is a cross-sectional side view of another embodiment of the invention.

Figure 4 is a cross-sectional side view of a third apparatus of the invention.

20

Figure 5 is a cross-sectional side view of a fourth embodiment of the invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring to Figure 1, there is shown a polishing device of the invention. An abrasive containing magneto-
25 rheological polishing fluid (MP-fluid) 11 is contained in a vessel 12.

The MP-fluid can contain a magnetorheological fluid and optionally, an abrasive medium. In a particularly

preferred embodiment MP-fluid is only magnetorheological fluid without any additional abrasive medium.

MP-Fluid 11 preferably has a composition as described in greater detail below. Vessel 12 preferably is
5 constructed of a non-magnetic material and is inert to the MP-fluid. A work-piece 14 to be polished is connected to a rotatable spindle 16. Spindle 16 is preferably made from a non-magnetic material. Vessel 12 preferably is semi-cylindrically shaped in cross-section particularly where work-
10 piece 14 is convexly shaped, as can be seen in Figure 1, and preferably is a circular annulus when viewed from above, as can be seen in Figure 2. However, the particular shape of vessel 12 can be modified to suit the particular work-piece desired to be polished, as can be seen in Figure 4. Movement
15 of vessel 12 is controlled by spindle 18, which preferably is positioned in a central location below vessel 12. Spindle 18 can be driven by a conventional motor or other power source.

An electromagnet 20 is positioned adjacent to vessel 12 so as to be capable of influencing MP-fluid 11 in a region
20 containing work-piece 14. Magnet 20 should be capable of inducing a magnetic field sufficient to carry out the polishing operation, and preferably will induce a magnetic field of at least about 50 kA/m. Electromagnet 20 is activated by magnetic windings 22, 24. Windings 22 and 24 can
25 be any conventional magnetic winding.

In operation, polishing device 10 operates as follows. Work-piece 14 is coupled to spindle 16, and positioned so that the portion of work-piece 14 to be polished

is in contact with MP-fluid 11 such as by immersing the work-piece in MP-fluid 11. Preferably, both work-piece 14 and vessel 12 are both put into rotating motion. A power source is activated to drive spindle 18 into rotating motion, thereby
5 rotating vessel 12. Spindle 18 rotates about a central axis 26 and preferably rotates vessel 12 at a speed insufficient to generate a centrifugal force which would eject or spray MP-fluid 11 out of vessel 12.

Spindle 16 is also rotated, about a central axis 28,
10 to provide rotating movement to work-piece 14. Preferably, spindle 16 operates at speeds of up to 100,000 rpm with about 2,000 rpm particularly preferred. The motion of spindle 16 provides continuous translational MP-fluid motion relative to the surface being polished.

15 Windings 22, 24 are activated to induce a magnetic field and influence MP-fluid 11. Preferably, MP-fluid 11 is acted on by a non-uniform magnetic field in a region adjacent to the work-piece 14 that is, equal-intensity lines of the field are equidistant to the surface of the work-piece, and
20 the force of the magnetic field is a gradient directed to the vessel bottom normal to the surface. Application of a magnetic field from magnet 20 causes the magnetorheological fluid to change its viscosity and plasticity. Magnetic particles present in the magnetorheological fluid become
25 aligned along force lines of the magnetic field thereby imparting higher effective viscous, plastic, and elastic properties to the magnetorheological fluid. As the abrasive particles contact work-piece 14, the surface of the work-piece

is gradually polished.

In an alternate embodiment of the invention, to increase the speed at which vessel 12 may be rotated without spraying MP-fluid 11 out of the vessel, vessel 12 can be tilted at an angle α to a horizontal plane. Referring to Figure 3, vessel 12 may be attached by means of a hinge 30 allowing vessel 12 to tilt at an angle α . Preferably, the angle of the tilt is less than about 90°, with about 45° particularly preferred.

Referring to Figure 4, there is shown an alternate embodiment of the invention. Figure 4 illustrates modifications to the vessel 12 in which the shape of the vessel is rectangular in cross-section rather than semi-cylindrical. This modification allows for more efficient polishing of a flat work-piece 14, such as a semiconductors. The tips of the magnetic poles 20, are shaped such that a nonuniform magnetic field is applied across the work-piece 14. In particular, the tips of the magnet can be angled toward work-piece 14. The angling can be provided in the manufacture of the magnet, or by attaching a detachable angular section to a magnet such as that depicted in Figure 1. The angled attachable section can be fastened to magnet 20 by, for example, screwing a triangular section onto magnet 20. In all other respects the embodiment depicted in Figure 4 is the same as that depicted in Figure 1.

Referring to Figure 5, there is shown a device useful for polishing inner surfaces of tubes. A tube work-piece 34 contains a volume of MP-fluid 11. Pump 32 is

connected via lines 38 to the inner portion of work-piece 34. Seals 40 provide a closed fluid loop between lines 38, pump 32 and work-piece 34. The tube work-piece 34 is placed between the pole pieces of electromagnet 36. The tube work-piece is placed in contact with a friction unit 44. Friction unit 44 is mounted upon shaft 46 which may rotate about its axis 48.

In operation, the polishing device operates as follows. Work-piece 34 is connected to lines 38 and the MP-fluid is pumped by pump 32 through work-piece 34. Work-piece 34 is rotated about its central axis 42 by friction unit 44 which rotates about axis 48 and is brought into contact with work-piece 34. A non-uniform magnetic field is created by pole pieces 36, and is applied to the MP-fluid passing through work-piece 34. Preferably, the magnetic field varies in time. The magnetic field is not applied while the MP-fluid is being pumped, allowing easy flow of the MP-fluid. The magnetic field is applied while MP-fluid is not being pumped through work-piece 34, allowing the formation of a closely fitted polishing tool against the inner surface of the work-piece 34.

Preferably, the electromagnetic pole pieces 36 are located along the axis 42 of the tube work-piece 34 equidistant from work-piece 34.

The composition of MP-fluid 11 preferably minimizes sedimentation and aggregation of the particles in the fluid. The MP-fluid may contain one or more thickening agents and/or surfactants to limit particle sedimentation and aggregation. Preferably, thickening agents may also impart thixotropic properties to the MP-fluid. Preferably, the MP-fluid contains

magnetorheological fluid which is mixed with an abrasive medium.

The magnetorheological fluid may comprise magnetic particles, a stabilizer, and a carrying fluid. The carrying fluid is preferably water. Preferably, a magnetorheological fluid has the following composition.

	<u>Component</u>	<u>Weight Percent</u>
10	Carbonyl iron powder	30.0-70.0
	Aerosil	0-4.4
	Glycerin	0-13.0
	Water	Balance

In a particularly preferred embodiment, the abrasive medium is immiscible with the magnetorheological fluid. In this embodiment the magnetorheological fluid preferably is of a composition such as those described in co-pending application Serial No. 868,466 filed April 14, 1992, whose disclosure is incorporated herein by reference. The carrying fluid in this embodiment preferably comprises an aromatic alcohol, a vinyl-alkyl ether, and kerosene. A particularly preferred magnetorheological fluid has the following composition.

Preferably, the magnetic particles are made from carbonyl iron and have a diameter of about 1 to 10 μm in diameter.

	<u>Component</u>	<u>Weight Percent</u>
30	Carbonyl iron powder	50-70
	Vinyl-n-butyl polymer ether	1.83-3.02
	α -naphthanol	0.013-0.020

Aerosil
Kerosene

4.5-7.5
Balance

Preferably, the abrasive medium is a liquid
5 suspension of abrasive particles. A preferred suspension
contains a water suspension of an abrasive powder sold under
the tradename POLIRIT (PF-O), manufactured by Plant of
Polirits, Narva, Estonia. POLIRIT (PF-O) is produced from a
mineral called laporit. POLIRIT is a mixture of the following
10 components, plus trace amounts of oxides of elements such as
Sm, It, Gd:

	<u>Weight percent</u>
	CeO ₂ 46-56
	La ₂ O ₃ 25-35
15	Ne ₂ O ₃ 13-18
	Pr ₆ O ₁₁ 3-4

Other preferred abrasive powders are: DIAMOND
powder (ASM (2/1) (manufactured by Plant optical mechanics,
Rostove Veliki, Russia); electrocorrund (Al₂O₃); and silicon
20 dioxide (SiO₂). Other suitable solvents include acids,
solutions of salts, bases and water. The choice of solvent is
dependent upon the properties of the work-piece 14. The
solvent can be chosen such that it is inert to work-piece 14
or, preferably so that it will chemically react with or
25 otherwise soften the surface of the work-piece 14. In this
preferred embodiment, reaction of the solvent with the surface
of work-piece 14 can substantially shorten polishing time.

In an alternate embodiment of the invention, the MP-
fluid components can be dispersed within each other by, for

example, ultrasonic dispersion techniques prior to delivery of the MP-fluid to vessel 12. This embodiment yields a more uniform fluid composition and minimizes the adverse effects of the immiscibility of the magnetorheological fluid and the abrasive medium. In this embodiment, the abrasive medium is injected into the magnetorheological fluid and this admixture is subjected to dispersion by an ultrasonic disperser. A preferred composition is:

10	<u>Component</u>	<u>Weight Percentage</u>
	POLIRIT	11.7-17.45
	Carbonyl iron	27.9-56.12
	Vinyl-n-butyl polymer ether	0.96-1.83
15	α -naphthanol	0.0064-0.013
	Kerosene	12.33-23.63
	Sodium salt of dodecylsulphacid	0.033-0.05
	Aerosil	2.34-4.49
	Water	Balance

20

In a third alternate embodiment of the invention, suspensions of abrasive particles (abrasive medium) and carbonyl iron powder (magnetorheological fluid) are prepared separately. A suspension of POLIRIT abrasive is prepared in an aqueous solution of a sodium salt of dodecylsulphacid. A preferred composition is:

30	<u>Component</u>	<u>Weight Percentage</u>
	POLIRIT	24.0-71.0
	Dodecylsulphacid	0-0.1
	Water	Balance

The carbonyl iron powder is suspended in a kerosene based dispersion medium. The dispersion medium may have a gel like consistency. A preferred composition is:

	<u>Component</u>	<u>Weight Percentage</u>
	Carbonyl iron powder	50.0-70.0
	Aerosil	4.5-7.5
5	Carrying fluid	22.5-45.5
	comprising:	
	polyvinyl-n-butyl ether	1.83-3.02
	α -naphthanol	0.013-0.020
	kerosene	96.96-98.157

The two prepared suspensions are placed in vessel 12
 10 separately prior to polishing. In operation, the two fluids
 mix to form a MP-fluid.

A particularly preferred composition of this sort
 is:

	<u>Component</u>	<u>Weight Percentage</u>
15	Carbonyl iron powder	56.12
	Aerosil	2.34
	Polymer of vinyl-n-butyl ether	0.96
	α -naphthanol	0.0064
	Kerosene	12.33
20	Sodium salt of dodecylsulphacid	0.033
	POLIRIT	11.7
	Water	16.5106

The cutting of a surface of a work-piece that occurs
 25 when there is relative movement between the work-piece and the
 MP-fluid is due to the contact of the abrasive particles with
 the work-piece. The abrasive particles are held in position
 relative to the work-piece by the magnetorheological fluid.
 By varying the effective viscosity, plasticity, and elasticity
 30 of the magneto- rheological fluid, the rigidity of the matrix
 holding the abrasive particle may be changed, thus varying the
 level of cutting force applied to the work-piece. Controlling
 the interaction between the abrasive particles and the work-
 piece by interaction of the magnetic particles and a magnetic
 35 field, allows for precise and nearly infinite regulation of

the interaction between work-piece and abrasive.

The use of MP-fluid also provides effective heat dissipation due to the convective heat removal. This allows polishing to be carried out under intensive operating
5 conditions with a reduced likelihood of thermal damage in the work-piece.

Moreover, upon action of the incoming flow, the magnetic field and the friction of the lower fluid layers against the rotating vessel surface, the magnetorheological
10 fluid is put into rotation in the polishing region. The axis of the observed rotation of the magnetorheological fluid volume is normal to the flow direction.

Thus, the control of the abrasive properties of the MP-fluid is determined by two factors: force and structure.
15 The effect of a nonuniform magnetic field provides a polishing zone where an elastic polishing instrument is formed. This also provides thrust toward the surface to be finished which is controllable.

The structure factor is characterized by a magnetic
20 field affecting the rheological properties (such as plasticity and effective viscosity) of magnetorheological fluid and the mechanical abrasive properties of the MP-fluid, putting the abrasive particles into motion at the polishing site.

Coarse abrasive particles that may be present in the
25 abrasive filler cause little or no damage to the polished surface because the magnetorheological fluid-polishing instrument is soft and elastic, possessing plasticity. Therefore, the coarse abrasive is simply "immersed" into the

magnetorheological fluid as the fluid yields to the pressure of the particle when the particle comes into contact with the work-piece. This occurs before the particle cuts into the work-piece surface which would otherwise result in damage to the work-piece.

The translational and eddy motion of magnetorheological fluid 11 in vessel 12 results in convective heat removal from the treated surface of work-piece 14. Consequently fluid 11 can contact work-piece 14 at high velocities, decreasing polishing times as compared to conventional systems. Heat conduction of magnetorheological fluids increase in magnetic fields promoting an increase in conductive heat removal. The efficient removal of heat in accordance with the invention can be seen in the examples herein, in which no temperature increase of more than 0.1°C was observed.

The polishing devices of the invention permit polishing of flat, spherical, aspherical and inner tube surfaces. The nature of the fluid and the ability to change effective viscosity, plasticity, and elasticity permits the fluid to conform to the work-piece irrespective of the surface shape to be polished. This makes the polishing of complex-geometry surfaces possible. Additionally, formation of the polishing working surface shape may be regulated by varying the magnetic field topography.

The following examples are illustrative of the invention.

Example 1

A work-piece made from a parabolic glass K-8 (commercial mark CIS) lens 60 mm in diameter with a 56° slope was polished using a device as shown in Figure 1 and described herein. Before polishing, the work-piece was preliminarily ground on a device ("TRIOTA", Germany), to an initial surface roughness of $R_a = 0.4\mu\text{m}$. The lens was attached to a spindle and positioned in the MP-fluid described below. The work-piece and vessel were each rotated and a magnetic field was applied to the fluid, until the lens was polished sufficiently. Polishing time was about 90 minutes. The vessel rotation speed was about 150 rpm, with the vessel radius equal to about 145 mm. The work-piece rotation speed was about 400 rpm. The magnetic field intensity near the work-piece surface was about 350 kA/m. An aqueous-glycerin mixture-based magnetorheological polishing fluid was used, having the following composition:

	<u>Component</u>	<u>Weight Percentage</u>
20	POLIRIT	1.53-35.9
	Carbonyl iron powder	27.7-69.8
	Aerosil	0-3.87
	Glycerin	0-12.55
25	Distilled water with chemical surface activator	balance

A final roughness value after treatment was $R_a = 12\text{\AA}$. The polishing rate was $0.8\mu\text{m}/\text{min}$.

Example 2

A flat work-piece made from gallium arsenide (GaAs),

with a diameter of 40 mm and a thickness of 400 μm was polished using a device shown in Figure 1 and described herein. Before polishing, the work-piece was preliminary ground on a device ("MULTIPOL", France) to an initial surface roughness of $R_a = 0.5 \mu\text{m}$. The gallium arsenide disc was attached to a spindle and positioned in the MP-fluid described below. The work-piece and vessel were each rotated and a magnetic field was applied to the fluid, until the disc was polished sufficiently. The vessel rotation speed was about 120 rpm and the work-piece rotation speed was about 20 rpm. The intensity of the magnetic field near the work-piece surface was about 200 kA/m. An aqueous glycerin mixture-based magnetorheological polishing fluid was used having the following composition: (Silicon carbide (SiC , particle sizes 0.4-1.0 μm) served as the abrasive filler.)

	<u>Component</u>	<u>Weight Percentage</u>
	Carbonyl iron	40.0
	Aerosil	1.7
20	Abrasive	2.6
	Glycerin	5.71
	Tartaric acid ($\text{H}_2\text{C}_4\text{O}_6$)	1.45
	Hydrogen peroxide (H_2O_2)	0.39
	Ammonia (NH_3)	0.15
25	Distilled water	48.0

The roughness value after treatment was $R_a = 20\text{\AA}$. The polishing rate was 0.7 $\mu\text{m}/\text{min}$.

30 Example 3

A tube work-piece made from nonmagnetic stainless steel (Russian commercial mark 12X 18H 10T) with an inside

diameter of 12 mm and an outside diameter of 16 mm was polished using a device as shown in Figure 5 and described herein. Before polishing, the work-piece was electrochemically treated with 100% nitric acid (HNO_3) to an initial surface roughness of $R_a = 0.22 \mu\text{m}$. The tube was installed between the poles of an electromagnet. The tube was filled with MP-fluid and rotated and oscillated along its axis. A magnetic field was applied. The tube rotation speed was about 1500 rpm, with an oscillation displacement of about 150 mm and an oscillation speed of about 0.3 m/minute. The magnetic field intensity near the work-piece surface was about 600 kA/m. The polishing time was about 110 minutes. A kerosene mixture-based magnetorheological fluid was used having the following composition: (Electrocorrund (Al_2O_3 , particle sizes 3-10 μm) served as the abrasive filler)

	<u>Component</u>	<u>Weight Percentage</u>
	Carbonyl iron	56.95
	Aerosil	2.34
20	Polymer of vinyl-n-butyl ether	2.3635
	α -naphthanol	0.0165
	Kerosene	30.33
	Abrasive	8.0
25	The final roughness value after treatment was $R_a = 0.032 \mu\text{m}$.	

WHAT IS CLAIMED IS:

1. A method of polishing an object comprising the steps of bringing said object into contact with a fluid; moving at least one of said object and said fluid with respect to the other; and varying the consistency of said fluid in a region wherein said object is located.
2. The method of Claim 1 wherein said fluid movement is past said object.
3. The method of Claim 1 wherein said object is mounted on a movable spindle adapted for positioning said mounted object into contact with said fluid.
4. The method of Claim 3 wherein the consistency of said fluid is varied by subjecting said fluid to a magnetic field.
5. The method of Claim 4 wherein said varied consistency of said fluid is exhibited by a change in effective viscosity, plasticity and elasticity of said fluid.
6. The method of Claim 4 wherein said magnetic field is a nonuniform magnetic field having equal intensity lines which are equidistant to the surface of said object.
7. The method of Claim 4 wherein said fluid forms an elastic polishing instrument in the presence of said magnetic field.
8. The method of Claim 1 wherein said fluid comprises a plurality of ferromagnetic particles, a stabilizer and a carrying fluid selected from the group consisting of water and glycerin in proportions sufficient to provide substantially no agglomeration or sedimentation of said magnetic particles.

9. The method of Claim 1 wherein said fluid comprises a plurality of ferromagnetic particles, a stabilizer and a carrying fluid comprising of an aromatic alcohol, a vinyl ether, an organic solvent and a compound selected from the group consisting of water and glycerin and mixtures thereof in proportions sufficient to provide substantially no agglomeration or sedimentation of said magnetic particles.

10. The method of Claim 9 wherein said stabilizer is aerosil, said aromatic alcohol is α -naphthanol, said vinyl ether is polyvinyl-n-butyl ether and said organic solvent is kerosene.

11. The method of Claim 1 wherein said fluid composition comprises:

- (a) 50 to 70 weight percent carbonyl iron particles;
- (b) 4.5 to 7.5 weight percent of aerosil; and
- (c) 22.5 to 45.5 weight percent of a carrying fluid comprising 1.83 to 3.02 weight percent polyvinyl-n-butyl ether, 0.013 to 0.020 weight percent α -naphthanol and 96.96 to 98.157 weight percent kerosene.

12. The method of Claim 9 wherein said fluid composition further comprises an abrasive particle powder.

13. The method of Claim 12 wherein said abrasive particle powder has a particle size of 0.001 to 100 μ m.

14. The method of Claim 13 wherein said abrasive particle powder is a micro-diamond powder.

15. A polishing device comprising:

- (a) a vessel for holding a polishing fluid;
- (b) a mount for receiving an object to be polished, said

mount adapted for positioning said object in contact with said fluid;

(c) means for moving at least one of said fluid and said mount with respect to the other;

(d) means for varying the consistency of said fluid in a region containing said mount.

16. The polishing device of Claim 15 wherein said vessel is comprised of a non-magnetic material.

17. The polishing device of Claim 15 wherein said mount is comprised of a non-magnetic material.

18. The polishing device of Claim 16 wherein said vessel includes an annular cavity which contains said polishing fluid.

19. The polishing device of Claim 18 wherein said means for varying the consistency of said polishing fluid comprises an electromagnet at the location that said mount is immersed in said polishing fluid.

20. The polishing device of Claim 19 wherein said vessel is adapted for angular displacement to prevent said fluid from escaping from said vessel.

21. A magnetorheological fluid composition comprising a plurality of ferromagnetic particles, a stabilizer and a carrying fluid selected from the group consisting of water and glycerin in proportions sufficient to provide substantially no agglomeration or sedimentation of said magnetic particles.

22. A magnetorheological polishing fluid composition comprising a plurality of ferromagnetic particles, a stabilizer and a carrying fluid comprising an aromatic

alcohol, a vinyl ether and an organic solvent and a compound selected from the group consisting of water and glycerin and mixtures thereof in proportions sufficient to provide substantially no agglomeration or sedimentation of said magnetic particles.

23. The compositions according to Claim 22 wherein said stabilizer is aerosil, said aromatic alcohol is α -naphthanol, said vinyl ether is polyvinyl-n-butyl ether and said organic solvent is kerosene.

24. A composition according to Claim 21 wherein said ferromagnetic particles are made from carbonyl iron.

25. A composition according to Claim 22 wherein said fluid composition comprises:

- (a) 50 to 70 weight percent carbonyl iron particles;
- (b) 4.5 to 7.5 weight percent of aerosil; and
- (c) 22.5 to 45.5 weight percent of a carrying fluid comprising 1.83 to 3.02 weight percent polyvinyl-n-butyl ether, 0.013 to 0.020 weight percent α -naphthanol and 96.96 to 98.157 weight percent kerosene.

26. A composition according to Claim 22 wherein said fluid composition further comprises an abrasive particle powder.

27. A composition according to Claim 26 wherein said abrasive particle powder has a particle size of 0.001 to 100 μm .

28. A composition according to Claim 27 wherein said abrasive particle powder is a micro-diamond powder.

29. A method of polishing a tubular object comprising

the steps of contacting an internal surface of said tubular object with a fluid; moving at least one of said fluid and said tubular object with respect to the other; and varying the consistency of said fluid in the region wherein said fluid contacts said internal surface of said tubular object.

30. The method of Claim 29 wherein said varied consistency of said fluid is exhibited by a change in effective viscosity, plasticity and elasticity of said fluid.

31. The method of Claim 29 wherein said tubular object is rotatably mounted upon a device for delivering said fluid to said inner surface of said tubular object.

32. The method of Claim 31 wherein said tubular object is further slidably mounted upon said device for delivering said fluid to said inner surface of said tubular object.

33. The method of Claim 32 wherein the consistency of said fluid is varied by subjecting said fluid to a magnetic field.

34. The method of Claim 33 wherein said magnetic field is a nonuniform magnetic field having equal intensity lines which are equidistant to the surface of said tubular object.

35. The method of Claim 33 wherein said fluid forms an elastic polishing instrument in the presence of said magnetic field.

36. A polishing device comprising:

(a) a plurality of lines for delivering a polishing fluid to a tubular object to be polished.

(b) means for connecting said tubular object to be polished to said lines, said connection adapted so that said

tubular object may move slidably and rotatably.

(c) means for moving at least one of said fluid and said tubular object with respect to the other;

(d) means for varying the consistency of said fluid in a region containing said tubular object.

37. The polishing device of Claim 36 further comprising a means to pump said polishing fluid.

38. The polishing device of Claim 37 wherein said lines are connected to said pump and said tubular object.

39. The polishing device of Claim 36 wherein said means for varying the consistency of said polishing fluid comprises an electromagnet at the location that said mount is immersed in said polishing fluid.

40. The polishing device of Claim 39 further comprising a means by which to rotatably move said tubular object above the central axis of said tubular object.

41. The polishing device of Claim 40 further comprising a means by which to slidably move said tubular object along said central axis.

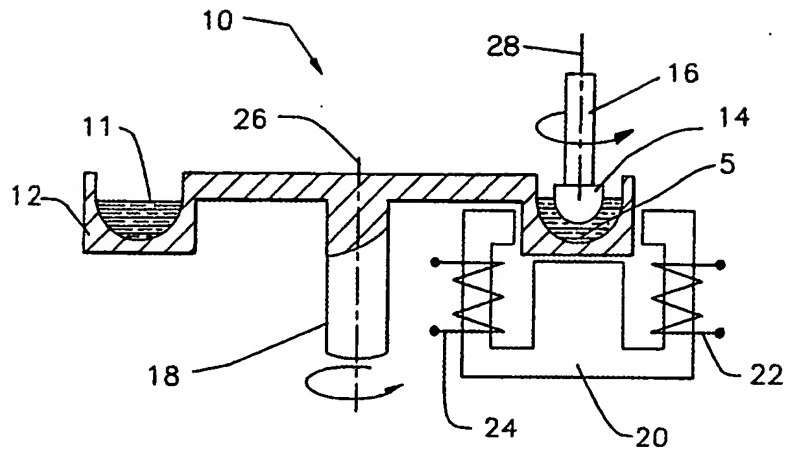


FIG. 1

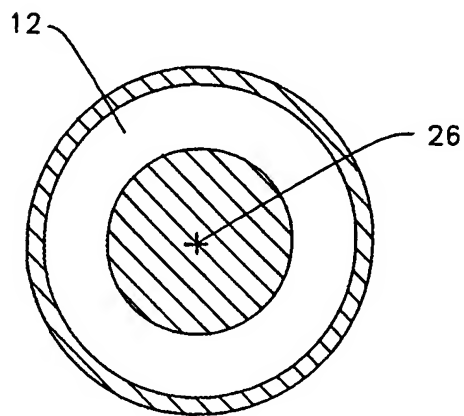


FIG. 2

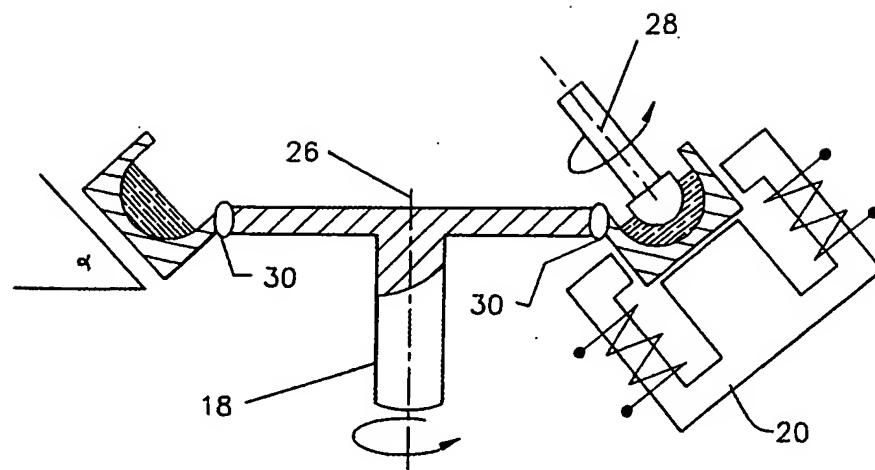


FIG. 3

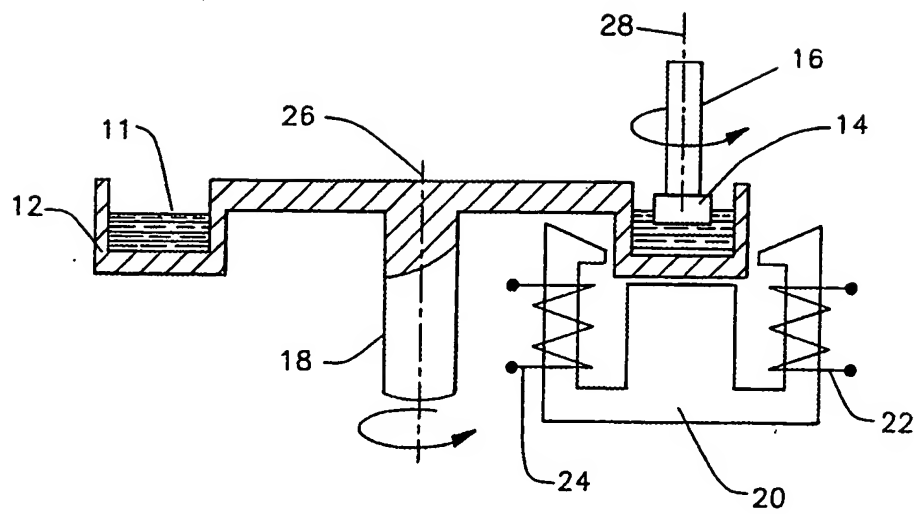


FIG. 4

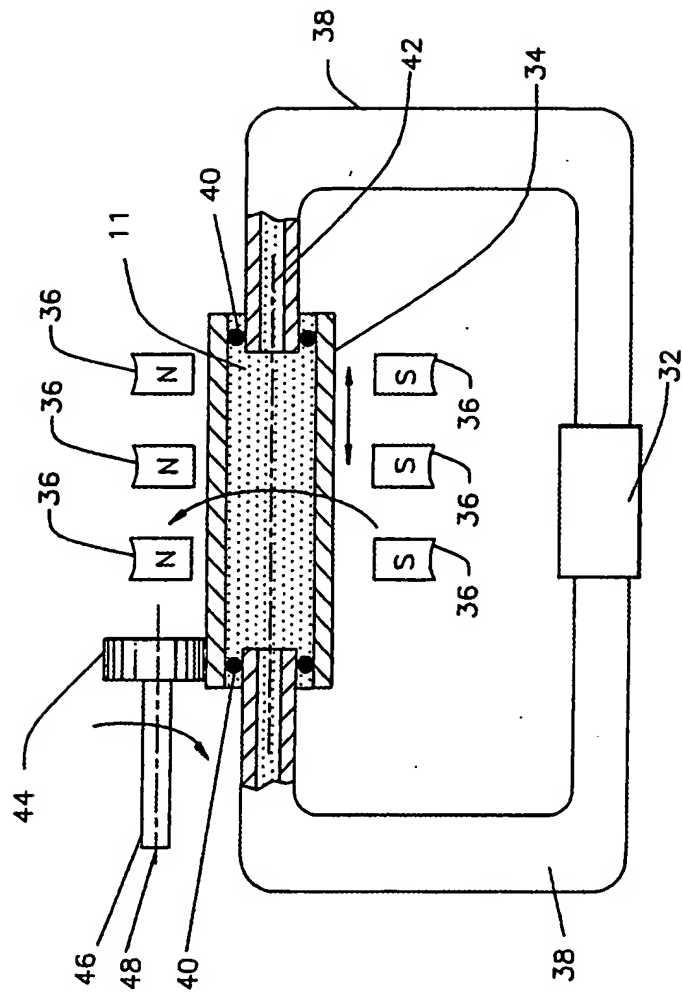


FIG. 5

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US93/07393

A. CLASSIFICATION OF SUBJECT MATTER

IPC(5) :B24B 39/02, 1/00

US CL :51/281p,317,7; 252/62.52,62.56

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 51/281P,317,7,6,17,318; 252/62.52,62.56,62.55,62.54

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X --- Y	US,A,4,821,466 (KATO ET AL.) 18 APRIL 1989 SEE ENTIRE DOCUMENT	1-7 ----- 8-10,12-14
Y	US,A,3,848,363 (LOVNESS ET AL.) 19 NOVEMBER 1974 SEE COLUMNS 2,4	8-10,12-14
X	DD,A,227,372 (FISCHER ET AL.) 18 SEPTEMBER 1985 SEE ABSTRACT	29-35
A	US,A,2,735,231 (SIMJIAN) 21 FEBRUARY 1956	ALL
X	RU,A,1,089,968 (KORDONSKY ET AL.) 03 APRIL 1984 SEE ENTIRE DOCUMENT	21-28

☒ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:	T	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
A document defining the general state of the art which is not considered to be part of particular relevance	X	document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
E earlier document published on or after the international filing date	Y	document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, each combination being obvious to a person skilled in the art
L document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	A*	document member of the same patent family
O document referring to an oral disclosure, use, exhibition or other means		
P document published prior to the international filing date but later than the priority date claimed		

Date of the actual completion of the international search

03 January 1994

Date of mailing of the international search report

02 FEB 1994

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INTERNATIONAL SEARCH REPORT

International application No.
PCT/US93/07393

Box I Observations where certain claims were found unsearchable (Continuation of item 1 of first sheet)

This international report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:
2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:
3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box II Observations where unity of invention is lacking (Continuation of item 2 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

Group I, Claims 1-14 and 29-35 are directed to a method of polishing, classified in class 51, subclass 317.
Group II, Claims 15-20 and 36-41 are directed to a polishing device, classified in class 51, subclass 7.
Group III, Claims 21-28, directed to a magnetorheological fluid, classified in class 252, subclass 62.51.

1. ☒ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.
2. ☐ As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of any additional fee.
3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:
4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

- ☐ The additional search fees were accompanied by the applicant's protest.
☐ No protest accompanied the payment of additional search fees.

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US93/07393

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	RU,A,1,154,938 (KORDONSKY ET AL.) 08 APRIL 1985	21-28
A	US,A,4,992,190 (SHTARKMAN) 12 FEBRUARY 1991	ALL
A	US,A,RE.32,573 (FURUMURA ET AL.) 05 JANUARY 1988	ALL
A	US,A,4,839,074 (ROSSI ET AL.) 13 JUNE 1989	ALL
A	US,A,3,897,350 (HEIBA ET AL.) 29 JULY 1975	ALL